ERDC TR-16-5

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Evaluation of *Rhizobium tropici*-derived Biopolymer for Erosion Control of Protective Berms

Field Study: Iowa Army Ammunition Plant

Steven Larson, Gary Nijak, Jr., Maureen Corcoran, Elizabeth Lord, and Catherine Nestler

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Final report

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Abstract

A *Rhizobium tropici* produced biopolymer was applied to an explosion protection berm at the Iowa Army Ammunition Plant (IAAAP) to stabilize the soil, prevent loss of berm height, reduce erosion, and increase the rate and extent of revegetation. The berm was recontoured, and a hydroseeder was used to apply biopolymer with grass seed. The control area received plain water and seed. Evaluated biopolymer application methods include single surface application, double surface application, and a double application at depth, with the first application 2-ft below ground surface (bgs), and the second on the surface. A LiDAR (Light Detection and Ranging) survey evaluated soil movement from the berm slope over three years. The double application of the biopolymer at depth was the most effective application method, as determined by calculating soil loss and surface roughness, followed closely by the double surface application. At 19 months post-treatment, a landslip was observed in the treated area that received the double surface application of the biopolymer. There was no evidence of soil cracking in any of the other treated areas. The slip appears to be due to an indentation in the crest of the berm that channeled runoff water into the area of the slip. Slope stabilization using biopolymer is approximately half the cost of construction and maintenance of traditional earthen berms over a 30-year period, due to lower installation and maintenance costs.

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Preface

The work reported herein was conducted at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. Funding was provided by the Environmental Security Technology Certification Program (ESTCP). The project was designated as ESTCP Project ER-0920.

This report documents a field demonstration of a biopolymer used to improve slope stability, decrease erosion, and induce rapid revegetation on disturbed soils. The site of the field demonstration was an explosion protection berm at the Iowa Army Ammunition Plant. Steven Larson and Elizabeth Lord of the ERDC Environmental Laboratory (EL), Environmental Engineering and Environmental Systems Branch, Maureen Corcoran of the ERDC Geotechnical and Structures Laboratory (GSL), Gary Nijak of Environmental Technology Services, Inc. (ETS), and Catherine Nestler of Applied Research Associates, Inc. (ARA), Vicksburg, MS, prepared this report. The report was reviewed by Stephen Pranger and Thomas Berry of ERDC-EL. The authors gratefully acknowledge the assistance provided by Elizabeth Lord and the LiDAR team from ERDC-EL Environmental Systems Branch.

This study was conducted under the direct supervision of W. Andy Martin, Chief, Environmental Engineering Branch, ERDC-EL and Warren P. Lorentz, Chief, Environmental Processes and Engineering Division, ERDC-EL; and under the general supervision of Dr. Pat Deliman, Technical Director, and Dr. Elizabeth Ferguson, Technical Director for Military Munitions in the Environment, ERDC-EL. Dr. Jack Davis was Deputy Director, ERDC-EL and Dr. Beth Fleming was Director, ERDC-EL.

COL Bryan Green was Commander of ERDC and Dr. Jeffery P. Holland was Director of ERDC.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	0.0254	meters
pints (U.S. liquid)	0.473176	liters
pounds (mass)	0.45359237	kilograms
quarts (U.S. liquid)	9.463529 E-04	cubic meters
square feet	0.09290304	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

Acronyms

ATCC	American Type Culture Collection
bgs	below ground surface
CRADA	Cooperative Research and Development Agreement
DOD	Department of Defense
EL	Environmental Laboratory
EPS	Extracellular polymeric substance
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
GAO	Government Accountability Office
GOCO	Government Owned - Contractor Operated
GSL	Geotechnical and Structures Laboratory
IAAAP	Iowa Army Ammunition Plant
LAP	Load Assemble Pack
LiDAR	Light Detection and Ranging
MSDS	Material Safety Data Sheet
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
PAM	Polyacrylamide
SAFR	Small arms firing range
USDA	United States Department of Agriculture
USPTO	United States Patent and Trademark Office

1 Introduction

1.1 Background

From the standpoint of installation management personnel, non-eroding soils for operational area berms are important as a means to provide facility noise control, as small arms firing ranges (SAFRs), explosion protection devices, and for water control. The methods currently used to reduce soil erosion from the berms include placement of geotextiles, use of vegetated areas, and the addition of soil modifiers.

Commercially, numerous products are available and used for soil strengthening (Tingle et al. 2007). There are two broad classes of soil stabilizers, the traditional (e.g., cement, lime, fly ash, and bitumen) and the non-traditional (e.g., lignosulfonates, enzymes, synthetic polymers, acids and fibers). These can be further broken down into binders (e.g., cement, fly ash, and synthetic polymers) that adhere to the soil (mainly a physical process) and reactants (e.g., lime, enzymes, lignosulfonates, and acids) that impart a chemical change to the soil. Reactants are usually limited to specific soil types that are amenable to a chemical change. Binders are more universal stabilizers for a variety of soil types, as they hold soil grains together and are not dependent on soil chemistry.

Most commercial soil-stabilizing emulsions are acrylic copolymers or copolymers of ethylene/vinyl acetate. In some cases, they improve the soil's engineering properties. Polyacrylamide (PAM) is an example of a commercial petroleum-based polymer used in agriculture to retain soil moisture and reduce erosion (Lentz et al. 2008, Zobeck and Schillinger 2010). Other commercial polymers available for dust control include SoilTac™ and DuraSoil™ (Newman et al. 2005, Tingle et al. 2007). However, the use of petroleum-based polymers has an increasingly negative public perception due to their limited biodegradability, petrochemical nature, and their tendency to leach toxic products into the soil (Lentz et al. 2008, Lucas et al. 2008, Weston et al. 2009). According to Executive Order 13423, "Strengthening Federal Environmental, Energy, and Transportation Management," Energy Independence and Security Act, the U.S. military is currently the nation's single largest consumer of petrochemicals. Under Department of Defense (DOD) Directive 4140.25, "DOD Management Policy for Energy Commodities and Related Services," Pentagon officials

projected total energy costs for 2007 at $13 billion and $20 billion for 2008. The Government Accountability Office (GAO) released report GAO-08-523T entitled "Defense Management: Overarching Organizational Framework Could Improve DOD's Management of Energy Reduction Efforts for Military Operations." Biopolymer technologies will replace the non-energy related petrochemical uses associated with polymeric chemicals, soil additives, and products that can be replaced with biologically produced polymers. The use of biopolymers also reduces the generation of hazardous substances associated with the design, manufacture, and use of the petroleum-based polymers currently in use, as well as the use of petroleum in general.

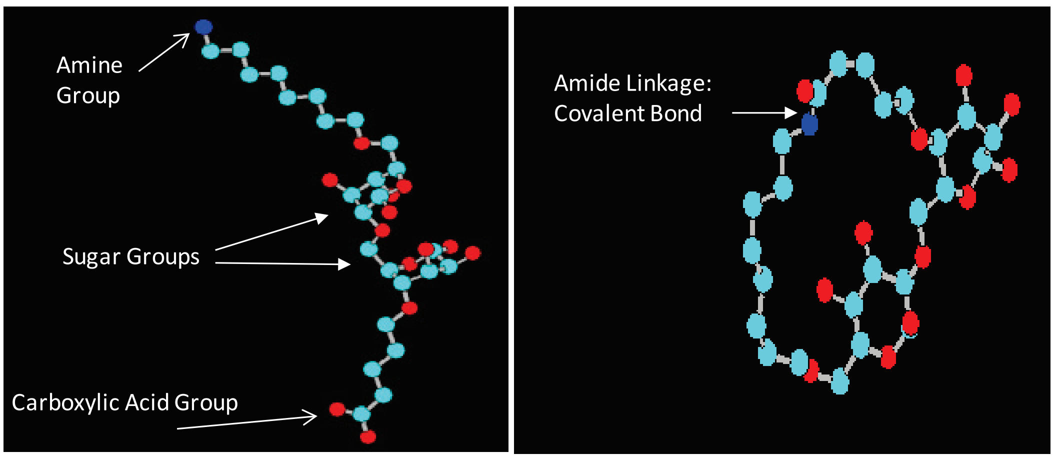
Rhizobium tropici ATCC® 49672, a catalogued symbiotic nodulator of leguminous plants (Martinez-Romero et al. 1991), is also known for its prolific production of a gel-like extracellular polymeric substance (EPS), a biopolymer (Gil-Serrano et al. 1990). Most of the *Rhizobium* EPS are polysaccharides containing glucuronic acid (Dudman et al. 1983a, 1983b, Franzen et al. 1983), although some exceptions to this basic structure have been reported (Amemura and Harada 1983, Gil-Serrano et al. 1990, Laspidou and Rittmann 2002). The natural functions of the EPS in the rhizosphere include surface adhesion between soil particles, self-adhesion of cells into biofilms, formation of protective barriers, water retention around roots, and nutrient accumulation (Laspidou and Rittmann 2002). Bacterial secretion of EPS is recognized as a cohesive force in promoting resistance to surface erosion in sediments (Droppo 2009, Gerbersdorf et al. 2008a, 2008b, Perkins et al. 2004, Stone et al. 2011). The function of bacterial EPS in promoting soil adhesion has been reported for several cyanobacteria (Hu et al. 2003) as well as for EPS in clay soil (Nugent et al. 2009). The adhesion, water retention, and protective biofilm qualities of the EPS from *R. tropici* suggests that the *R. tropici* EPS can be used to improve the strength of soil for erosion control and slope stability in situations where traditional techniques, such as geotextiles and simple vegetative cover, have proven to be ineffective.

1.2 Technology description

Both synthetic and biopolymers are made of repetitive monomeric units. The term "primary structure" is used to describe the chemical composition and the sequence of repeating units. Most synthetic polymers that are prepared using petroleum-based monomeric units have a much simpler, less varied structure. Typically, they consist of copolymers where the repeat

unit sequence is statistically controlled. In contrast, many biopolymers can fold into functionally compact shapes through cross-linking (via hydrogen bonding, hydrophobic associations, multivalent ion coordination, etc.) as shown in Figure 1-1. This changes not only their shape, but also their chemical properties. In addition, biopolymers often have complex pendant moieties that display highly specific functionalities. Unlike petroleum-based polymers with their uniform molecular structure and reactivity among monomers, one advantage of the biopolymer is the ability of the EPS to cross-link due to reactive moieties within a single polymeric component.

Figure 1-1. Schematic representation of biopolymer cross-linking at an amine group.



1.3 Approach

A technique has been developed through which an *R.tropici*-derived biopolymer can be produced in an aerobic bioreactor. The polymer is separated from the bacteria and the growth media, then derivatized in order to produce a non-reactive (non-cross-linking) material that can be transported as either a concentrated liquid or a low density, dry solid (Newman et al. 2010).

The biopolymer can be applied to the soil in dry form or pre-mixed with water and applied as slurry. If the biopolymer is reconstituted on-site, the water used does not need to be potable and can come from a “grey water” system, thus conserving water resources. When wetted, the biopolymer will form a gel within the soil matrix. With the soil acting as a buffer, the ionic character of the polymer salt is neutralized; then the polymer can begin to self-react and cross link to yield a form of the biopolymer that has a larger molecular weight and a reduced water affinity. Through this action, individual soil particles are linked together within the biopolymer

matrix. These linked soil particles have greatly reduced mobility and significantly reduced hydraulic conductivity. This change in the physical form of the soil, on a particle level, results in increased soil strength, reduced dust generation, and decreased erodibility (Larson et al. 2012).

The use of a biopolymer as a soil modifier for erosion control and sediment transport was evaluated through slope stability and surface soil durability studies at bench- and meso-scale (Larson et al. 2012). The studies were performed using silty sand and a silt soil characterized in Table 1-1. Larson et al. (2012) concluded that application of the biopolymer to soil at economically feasible loading rates could effectively maintain the slope stability of a simulated berm. In addition, the biopolymer was able to reduce the transport of soil particulates in runoff water from the berm. The biopolymer performed effectively when used with soils at high risk for erosion.

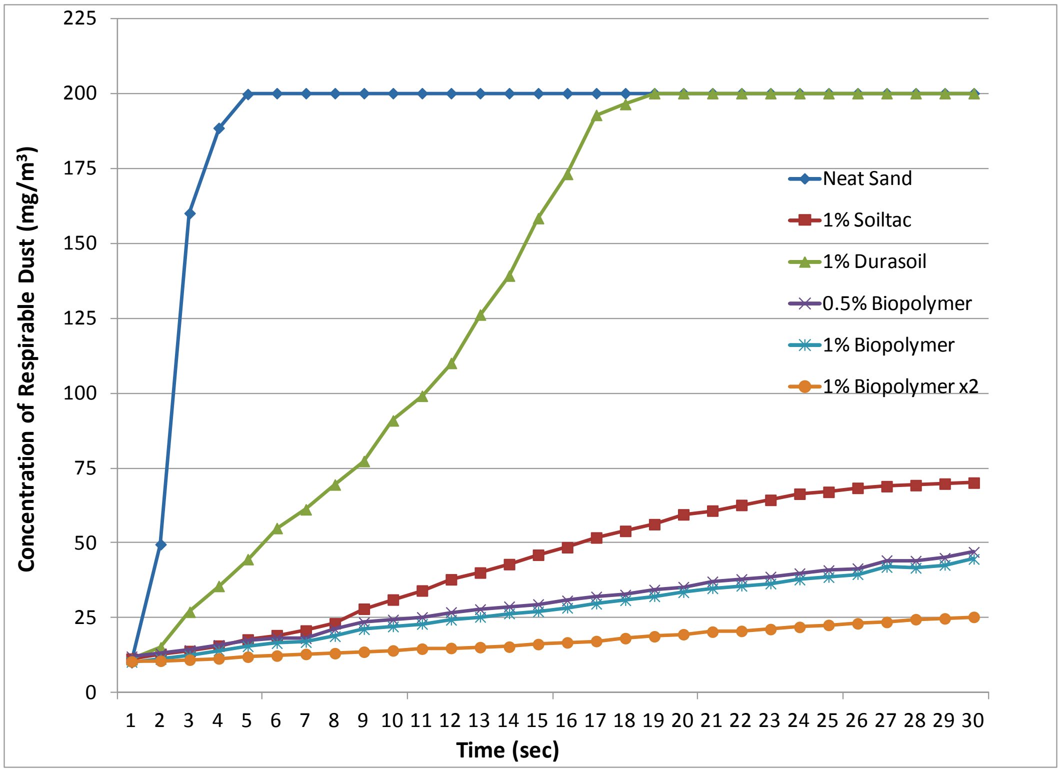
Table 1-1. Characteristics of soils employed in slope stability studies with *R. tropici* biopolymer.

Soil type	LL	PL	PI	Gravel (%)	Sand (%)	Fines (%)
Silty Sand (SM)	NP	NP	NP	0.5	77.2	22.3
Silt (S)	27	23	4	0	1.1	98.9

LL – liquid limit
PL – plastic limit
PI – plastic index
NP – non-plastic

The silty sand soil was also used for wind erosion studies (ESTCP symposium, 2011). The objective of the study was, first, to compare production of fugitive dust from soil treated with either the *R. tropici* biopolymer or a commercial dust inhibitor, and second, to examine the effect of biopolymer concentration and single *versus* double applications. Uncontaminated, washed and graded playground sand served as the control. The commercial products used for comparison were SoilTac™ and DuraSoil™ (Soilworks, LLC). The method is described in Rushing and Newman (2010). The results (Figure 1-2) show that the lowest concentration of respirable dust was produced by treating soil with either a single or a double application of biopolymer. The double application of the 1% concentration of biopolymer performed slightly better than the 0.5% or the 1% rates in a single application. The biopolymer outperformed the commercial petroleum-based polymers in all applications.

Figure 1-2. Comparison of the production of fugitive dust from silty sand after treatment with either commercial, petroleum-based, or biological polymer.



1.4 Demonstration objectives

The Army industrial base uses explosion control berms in areas where manufacturing and load-assemble-pack (LAP) activities present an explosion hazard. In the event of an explosion or fire on one production line, the berm prevents the spread to additional areas of the facility. Maintaining berm height is a critical parameter for explosion containment.

The overarching objective of the demonstration was to validate soil erosion control by the biopolymer in the field at full-scale, and transfer the technology to end users at Army industrial installations. Secondary objectives included:

- Evaluation of biopolymer application methods to determine which method is most cost effective and efficient,
- Evaluation of enhanced vegetative growth as a means for rapid repair of disturbed soils,
- Evaluation of the longevity of biopolymer-treated slopes.

2 Materials and Methods

2.1 Materials

2.1.1 Biopolymer

Environmental Technology Service, Inc. (ETS), a project partner, produced the biopolymer used in the IAAAP field demonstration. Four different batches of biopolymer (marketed through ETS as "GreenTac") were utilized for the IAAAP project. The project scope required GreenTac at a minimum specification of 8 g biopolymer/L. The total amount of biopolymer used was 11,000 gallons. The average composition was 12.9 g biopolymer/L. The biopolymer was shipped and applied in its liquid form. The Material Safety Data Sheet (MSDS) for GreenTac is available as Appendix A.

2.1.2 Site description

The Iowa Army Ammunition Plant (IAAAP) is an active, government-owned, contractor-operated (GOCO) facility in Des Moines County near Middletown in southeast Iowa. American Ordnance, LLC. operates the IAAAP. Active or formerly active munitions production or storage facilities occupy approximately 1/3 of the IAAAP property. Capabilities of the ammunition plant include LAP for a full range of munitions and high explosive components (www.globalsecurity.org).

The location of the IAAAP has a mean annual temperature of 51.8 °F. The average annual precipitation is 40.6 inches. Winters are generally mild. Snow is infrequent, but ice storms are common, with one or two destructive storms occurring each year. The potential for frost lasts through the middle of April. May and June are the months with normally high rainfall. In the six months between LiDAR evaluations (October 2011 to March 2012), the site received 12.3-in of rainfall and 9.4-in of snow. Total rainfall in 2012 was just over half of what is normally received in a year, making it a drier than normal year (National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center (NCDC), www.ncdc.noaa.gov). Total rainfall for 2012 and 2013 was 30.7-in and 37.6-in, respectively. Snowfall was also higher, 11.6-in and 17.6-in for 2012 and 2013, respectively. The third LiDAR evaluation was performed in September 2014. The IAAAP area had already experienced 31.8-in of rain and 43-in of snow since January 2014.

Hard fescue (*Festuca brevipila*) is the grass of choice in this area for re-vegetation following construction activity and stabilizing roadsides and ditch banks. Fescue is an introduced cool-season, fine-leaved perennial bunchgrass. It is long-lived, persistent, and competitive with other grasses and weeds (USDA, NRCS Plant Fact Sheet, http://plants.usda.gov).

2.1.3 Demonstration site

The selected biopolymer test site was Berm 03-50-A at the IAAAP. Figure 2-1 shows the condition of the berm prior to the field demonstration. Berm erosion and a series of small landslides had caused progressive collapse of the berm face and loss of protective height. Darker areas with no vegetation indicate the recent propagation of numerous small landslides into and across the slope. These led to a number of conditions that made the berm unusable, including reduced blast protection (as a result of loss of berm height), which is unsafe for berm vegetation management (e.g., mowing), as well as the potential for damage to surrounding buildings, roads, and drainage features.

Figure 2-1. Berm 03-50-A at IAAAP, showing loss of height, slope degradation and land slips on the face of the berm.

2.2 Methods

2.2.1 Berm reconstruction

To begin the reconstruction process, a bulldozer was used to remove the surface vegetation (Figure 2-2A), and then earth-moving equipment was

used to restructure the berm (Figure 2-2B and C). The completed berm is shown in Figure 2-2D. The silt fence, visible in Figure 2-2D, was used for containment until vegetation covered the berm face and reduced the potential for soil transport.

Figure 2-2. Steps in the reconstruction of Berm 03-50-A.

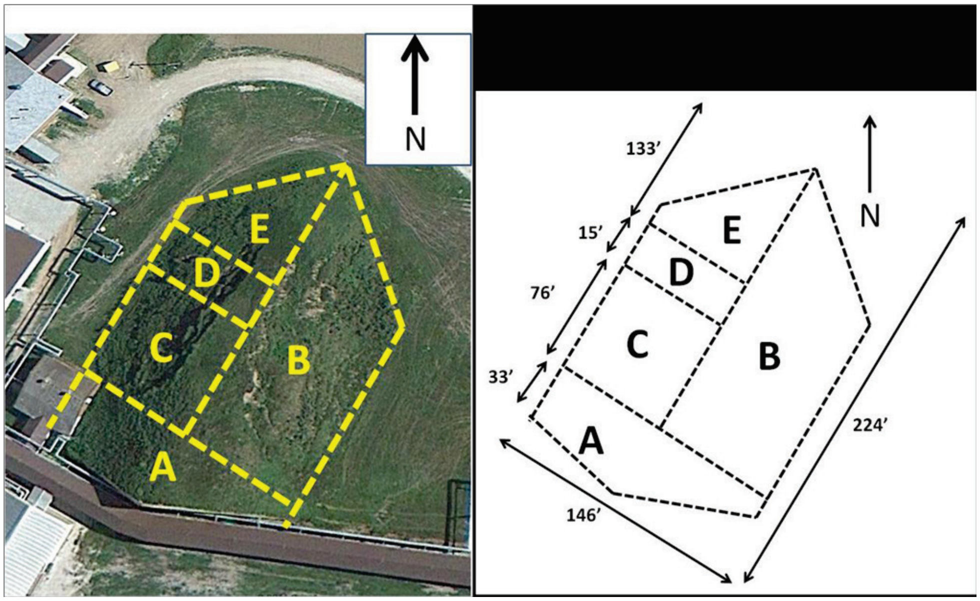
2.2.2 Biopolymer application

Several different application methods were used to evaluate biopolymer effectiveness at erosion control and revegetation following reconstruction of Berm 03-50-A at the IAAAP (Figure 2-3). The quantities of biopolymer used during application are listed in Table 2-1.

- Area A was left untouched during the course of the project to ensure safety of crewmembers and to prevent damage to the retaining wall next to Area A and the small building alongside the slope; however, the remainder of the berm was recontoured. Area A was not included in any erosion calculations.
- Area B was a steeper slope. Two feet of soil was removed from the surface, biopolymer was applied, the area was re-covered and then additional biopolymer and grass seed was applied (Double depth).
- Area C was a double surface spray application separated by 24-hours (Double).

- Area D was the control that received no biopolymer application (Control), simply grass seed and water.
- Area E was a single surface spray application (Single).

Figure 2-3. Site layout for evaluation of biopolymer application methods to Berm 03-50-A.



Key:
Area A: untouched
Area B: double depth application, first 2 ft bgs, second on surface
Area C: double surface application, separated by 24-hr
Area D: control, no biopolymer applied, just water and seed
Area E: single surface application

Table 2-1. Experimental design for biopolymer application rates.

Experimental site	Application 1	Application 2	Total Biopolymer Applied
B-Double application at depth	2,500 gal	2,500 gal (with seed)	5,000 gal
C-Double surface application	1,200 gal	500 gal (with seed)	1,700 gal
D- Control, no biopolymer	Water only (with seed)	NA	0 gal
E- Single surface application	2,700 gal (with seed)	NA	2,700 gal

NA: not applicable

The biopolymer was applied to the soil surface using a hydroseeder or a hand held water hose (Figure 2-4). The control area received only water and the same seed used on the experimental areas of the berm.

Figure 2-4. Application of biopolymer on the berm slopes.

2.2.3 LiDAR aquisition

LiDAR is an optical remote sensing technology that can measure the distance to, or other properties of, a target by illuminating the target with light, generally using pulses from a laser. It can map physical features with very high resolution. In this instance, it was used to detect changes in berm height and soil distribution on and around the berm in order to establish effects of biopolymer soil modification on soil erosion. The LiDAR used for the field demonstration was Trimble's FX terrestrial 3-D Laser Scanner (Figure 2-5). Instrument calibration followed manufacturer's guidelines. The light that this LiDAR system uses to measure the highly accurate X, Y, and Z data points is a 685 nm (red) laser beam.

The team set up four concrete hubs approximately 24 inches deep in order to be below the freeze line. Survey markers were placed on top of the conduit pipe placed in each concrete-filled hole. These markers, along with a nail placed in the top- center of the berm wall, were used as the survey controls. This type of permanent control is used in order to have constant reference points, thus getting the highest accuracy possible between survey dates. Traditional surveying techniques were performed using a robotic total station coupled with RTK (Real Time Kinematic) grade GPS (Global Positioning System) survey measurements each time the berm was measured.

Figure 2-5. LiDAR team setting up the laser tripod one month post-treatment.

For each survey period (i.e., 2011, 2012, 2014), two NGS OPUS (National Geodetic Survey – Online Positioning User Service) points were collected on two of the concrete markers. The points were measured using the RTK GPS receivers, and sent into the NGS OPUS service that produces extremely high-accuracy NSRS (National Spatial Reference System) coordinates.

Three LiDAR surveys were conducted on the berm. The first was in October of 2011, approximately one month after completion of the berm. The second survey was a re-scan in April 2012 (six months, post-treatment). The third was performed on August 31-Sept 3, 2014, 3-yr post-treatment. In order to collect these surveys, the instrument was set up on a tripod. Small spheres, used for registration between the scans, were set out on the berm (Figure 2-6). The instrument has a 360° x 270° field of view, and has the capability to capture over 200,000 points per second. Once a scan begins, the mirror inside the instrument begins to spin continuously, pulsing the laser beam until it has successfully collected the 3-D X, Y, Z data points as far as it can "see." Once the scan was completed, the next scan station location was selected, and the instrument was moved to the new location. Each new location had to be close enough to the previous scan station location that the scans would have common targets between them. Common targets allowed all the scans to be accurately merged together into one 3-D Data Cloud containing tens of millions of X, Y, Z data points.

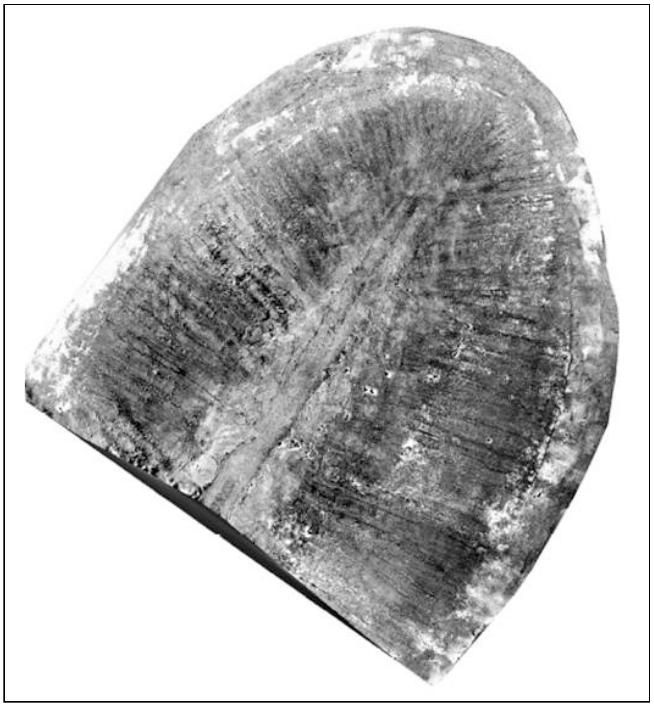
Figure 2-6. LiDAR registration spheres on the berm slope one month post-treatment with biopolymer and grass seed.

The laser is line of sight, with a single return, and does not penetrate materials. Therefore, having a clear line-of-sight is important for accurate repeated measurements. Grass was not an issue with the six-month scan, because while germination was obvious, growth was minimal over the winter months. After three years, the vegetation was substantial, and besides grass, included several small trees. An important aspect of the third survey was, therefore, grass-mowing, tree cutting, and raking to remove as many objects from the laser path as possible.

2.3 LiDAR Data Analysis

LiDAR analysis consisted of modeling the 3-D data collected during the initial, six month, and three year sampling trips. The point spacing collected varied with how close the laser was to what it was measuring. However, for modeling purposes the data was reduced to 2-cm point spacing on an equal interval grid, resulting in a grid point that was 2-cm vertically and 2-cm horizontally. All of the measurements and results were derived from the 2-cm data sampling (Figure 2-7). In a black and white scheme, the lighter areas are points of soil deposition, and the darker areas are points of soil loss.

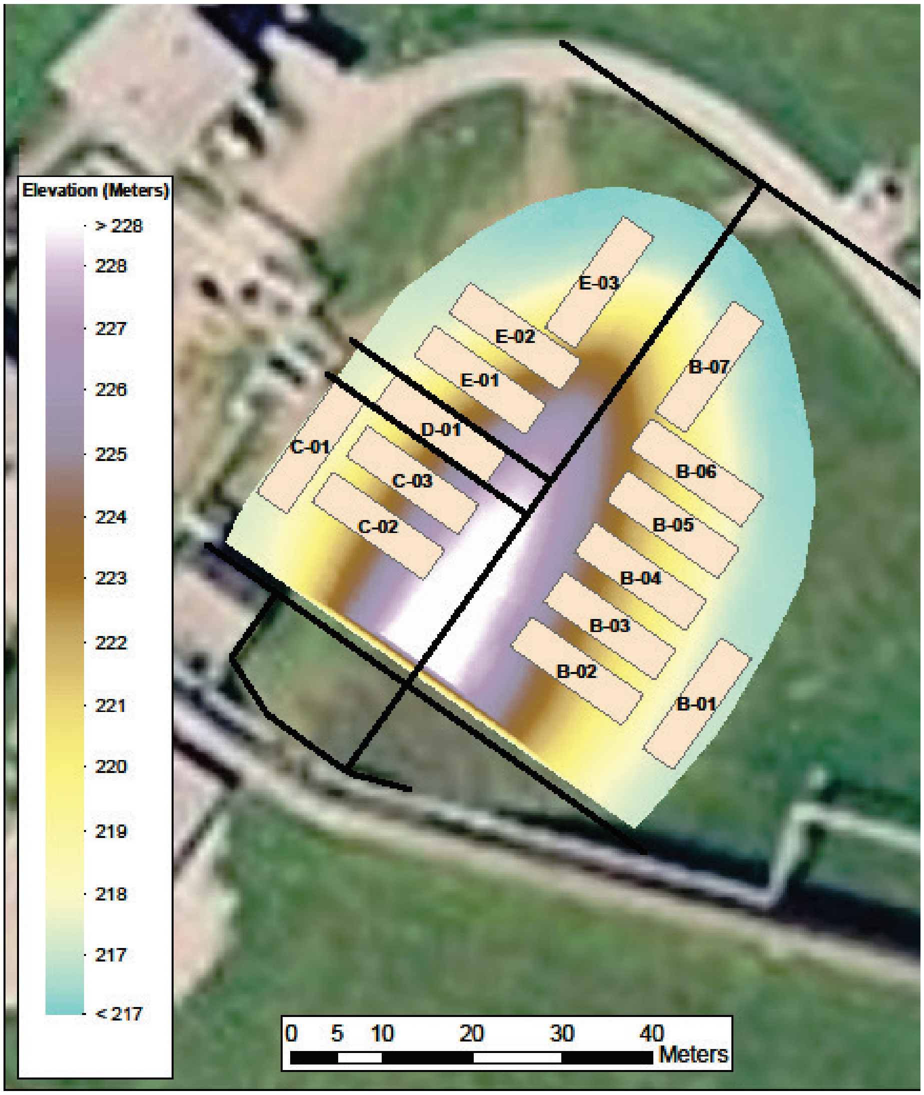
Figure 2-7. Results of the LiDAR initial survey based on the 2-cm x 2-cm scan.



Equal size rectangles in the application areas were superimposed on an image developed from the original survey (Figure 2-8). The same pixels in each rectangle were used to calculate changes in slope and elevation in each sampling event. Results were normalized to account for smaller and larger sample areas. ESRI's ARCMAP, version 10.0, using both the Spatial Analyst and 3-D Analyst extensions, was used to perform analysis on the 14 individual rectangles.

FXController software was used to collect the measurements with the laser scanner. Trimble's RealWorks Survey, version 7.0 software was used to join the scan data together with the registration spheres and apply the real world GPS coordinates to the point clouds. This software was also used to decimate the data clouds to the 2-cm point spacing that was used in ARCMAP.

Figure 2-8. LiDAR data analysis for each sampling event.



3 Field Demonstration Results

3.1 Vegetative growth

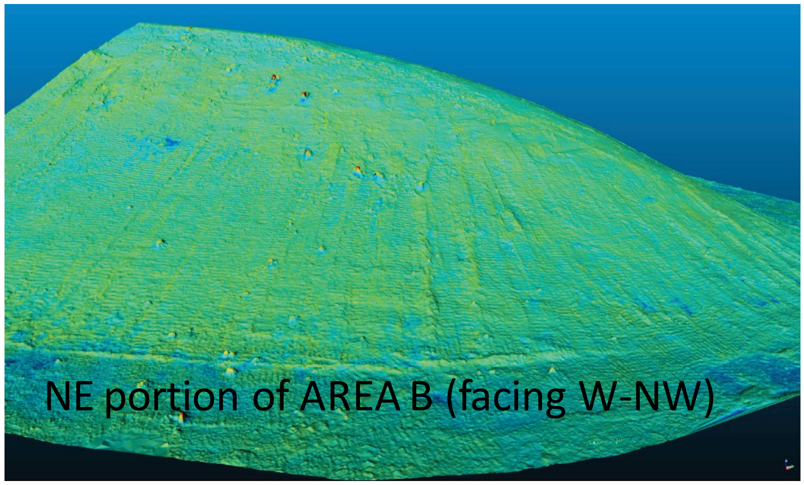
ETS, Inc. showed that the average biomass of the Fescue grass in the biopolymer treated areas increased 223% versus the control area, which was seeded with water but had no biopolymer. The ratio of root mass to the above ground plant mass was approximately 7% for the treated areas and 5% for the untreated soil. A photograph of the control next to a treated area illustrates the difference in grass growth at one month post-treatment (Figure 3-1).

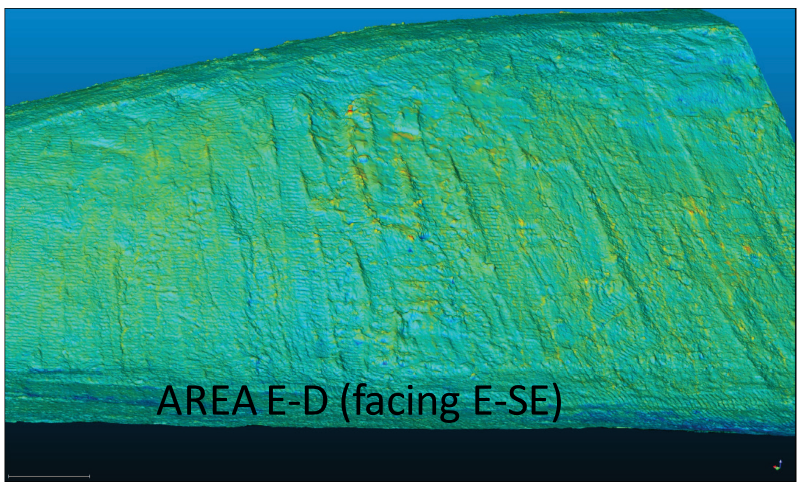
Figure 3-1. Comparison of surface rutting and vegetative growth after six months of weathering between the untreated control (Left) and the biopolymer-treated area (Right).

3.2 LiDAR Imaging

The biopolymer application areas from the experimental design are shown in Figure 2-3. An initial LiDAR image of the completed berm is shown in Figure 3-2. Data for this image was obtained one month post-treatment. Marks from the caterpillar tread were still visible on the biopolymer-treated soil surface.

Figure 3-2. Initial LiDAR image of the completed East face of Berm 03-50-A. Top: Area B-double application at depth: biopolymer treatment at 2 ft-bgs and surface). Bottom: Area E-D (single surface application of biopolymer, the untreated control, and the double surface application).





3.2.1 Change in berm elevation and redistribution of soil mass

Following six months of weathering (October 2012 to March 2013), the LiDAR team returned to IAAAP and re-measured the berm surface elevation using the original reference control points. Figure 3-3 provides a detailed view of the weathered West face of the berm. The red color indicates soil loss, marking the creation of erosion channels across the face of the berm.

A map was also constructed of surface elevation changes over the entire berm (Figure 3-4A). A similar map was produced in 2014 (Figure 3-4B). In these figures, the blue/green colors indicate degrees of soil gain and the yellow/orange/red colors indicate degrees of soil loss.

Figure 3-3. LiDAR image of berm West face (Area E-D) after six months of weathering.

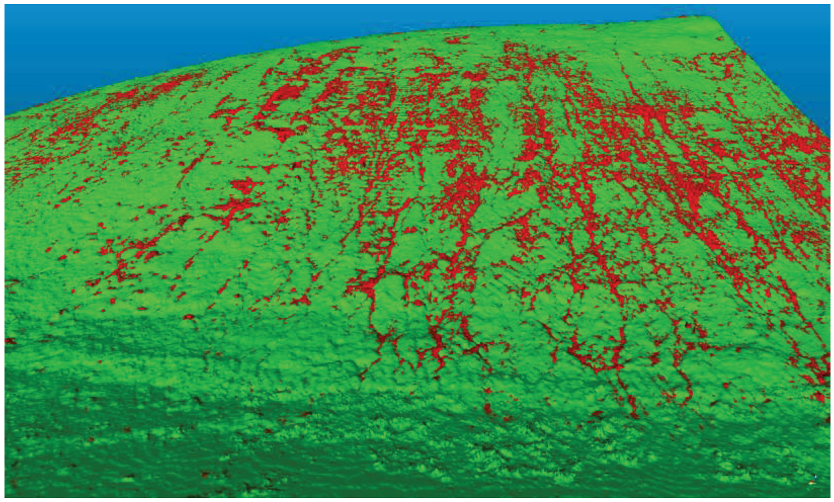
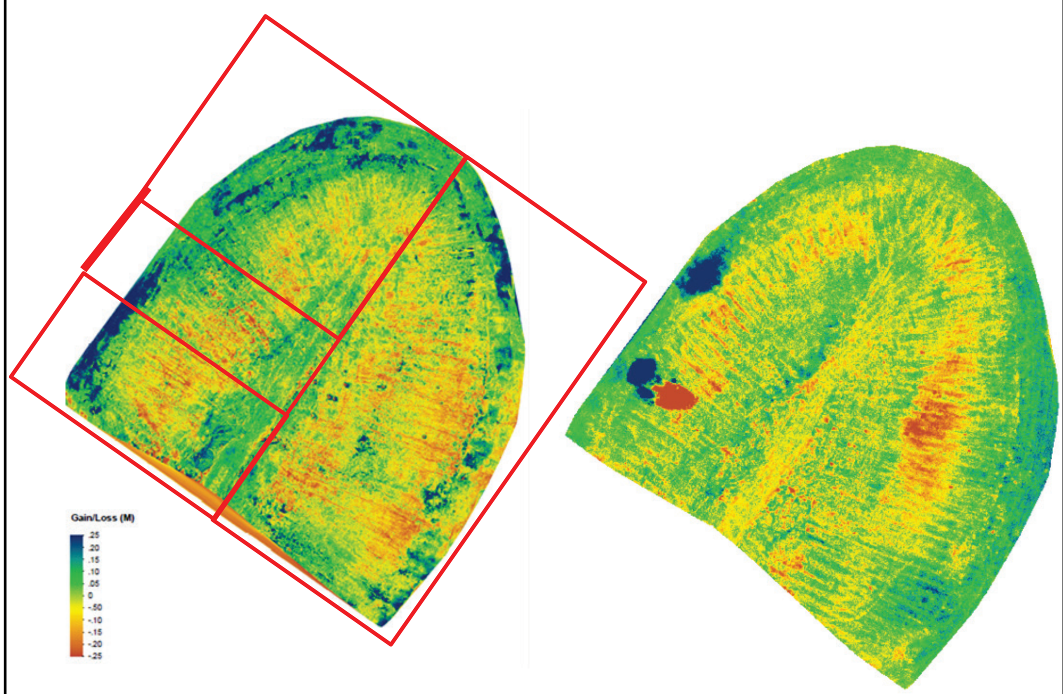


Figure 3-4. LiDAR image of the top view of berm showing changes in soil elevation (net gain and loss) by color differences (blue/green = soil gain, yellow/orange/red = soil loss).



A. Change detection between Oct 2011 and March 2012

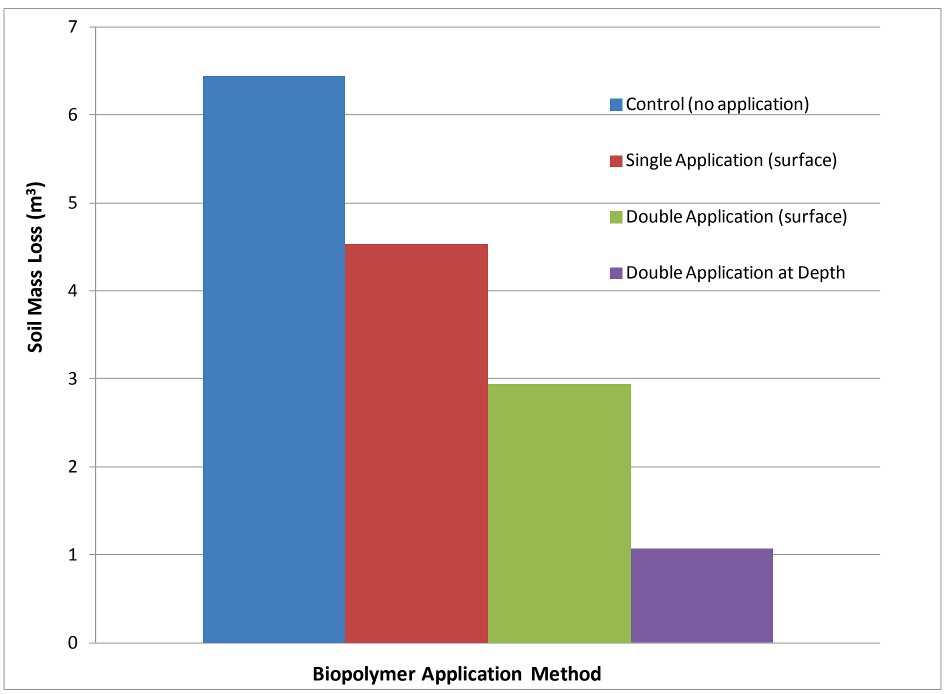
B. Change detection between March 2012 and Aug 2014

The pixels themselves were used to calculate the change in soil volume (mass lost) and elevation (roughness) in each area across the berm. At six months post-treatment, all changes are assumed to be the result of erosion. The six months between the first two LiDAR surveys were winter months

when grass was dormant. At the time of the six-month survey, the majority of the grass was still short and immature. Any taller stands between the data collections were trimmed to ground level. Therefore, vegetative growth was not factored into the calculations. After three years, the vegetation was substantial and, besides grass, included several small trees. An important aspect of the third survey was grass mowing, weed eating, tree cutting, and raking to remove as many objects from the laser path as possible.

The initial soil volume change during the first six months post treatment (expressed as soil mass lost) by biopolymer application method is shown in Figure 3-5. The least mass of soil lost was observed in the area treated twice with biopolymer, once at depth and the second time on the surface (16.56% loss compared to the control area). The greatest loss of soil mass was seen from the untreated control area.

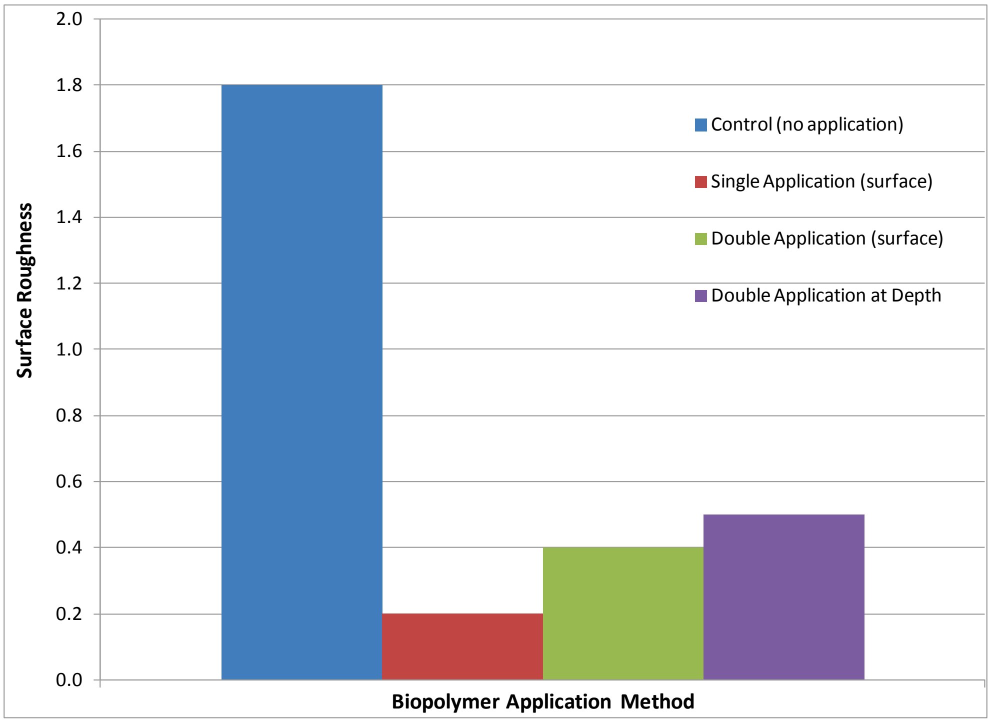
Figure 3-5. Comparison of biopolymer application method for soil mass lost over six months of weathering calculated through LiDAR imaging of the berm surface.



The initial change in surface elevation, expressed as roughness, was also compared between biopolymer application methods (Figure 3-6). The untreated control showed the greatest development of surface roughness. All biopolymer-treated areas were significantly smoother than the control. The smoothest surface was seen in the area treated with a single surface application of the biopolymer (Area E) at 11% of the control. However, the other treated areas also demonstrated very little change in soil elevation

over six months (22% and 28% of the control for double surface application (Area C) and double application at depth (Area B), respectively). The higher degree of roughness in Area B (double application at depth) could be attributed to settling of the disturbed lower layer of soil.

Figure 3-6. Comparison of biopolymer application method for changes in surface elevation (roughness).



Continued soil elevation changes are shown according to application method in Figure 3-7 and over time in Figure 3-8. As expected with weathering, there was a gradual smoothing of the soil surface over the entire berm over time, regardless of the method of biopolymer application. This is evident in the LiDAR images of the toe area of the berm, which shows Area B on the left of the image and Areas E, D (control), and C on the right side of the image (Figure 3-9).

3.2.2 Berm erosion

In May 2013, 19 months post-treatment, a small landslip was observed on the explosion protection berm in the area corresponding to Area C, the double surface application (Figure 3-10). The initial size of the collapse, was 11-ft wide by 25-ft long by 1-ft deep which yields a total displacement of 275 ft^3 of soil (Figure 3-11).

Figure 3-7. Change in surface roughness by application method.

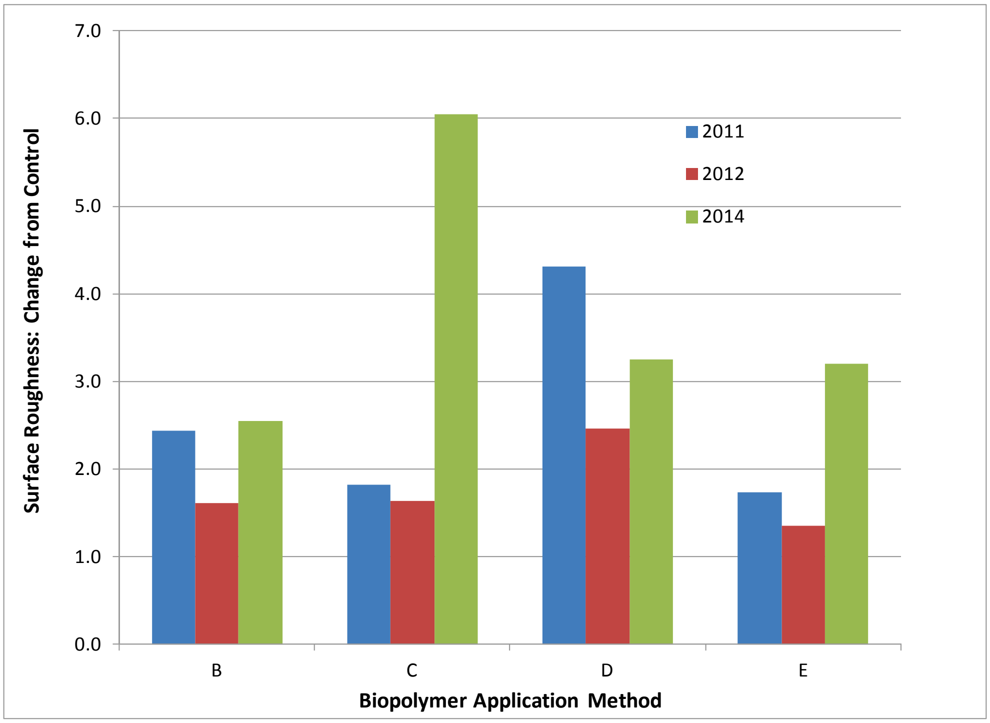


Figure 3-8. Changes in surface roughness over time.

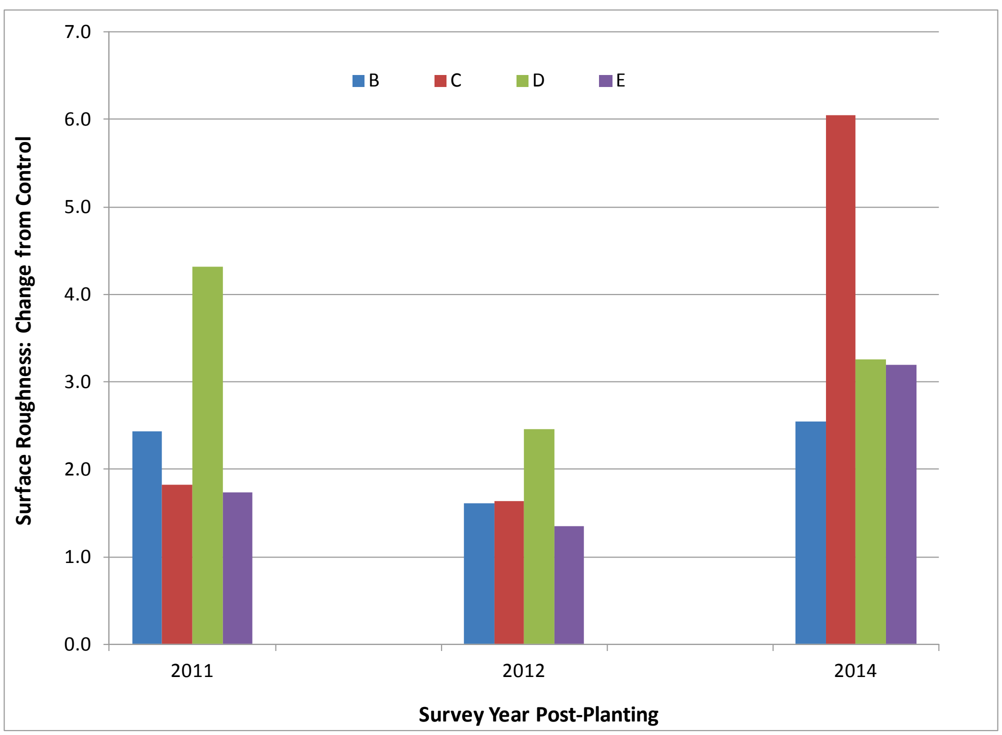


Figure 3-9. Leveling of the berm surface over time.

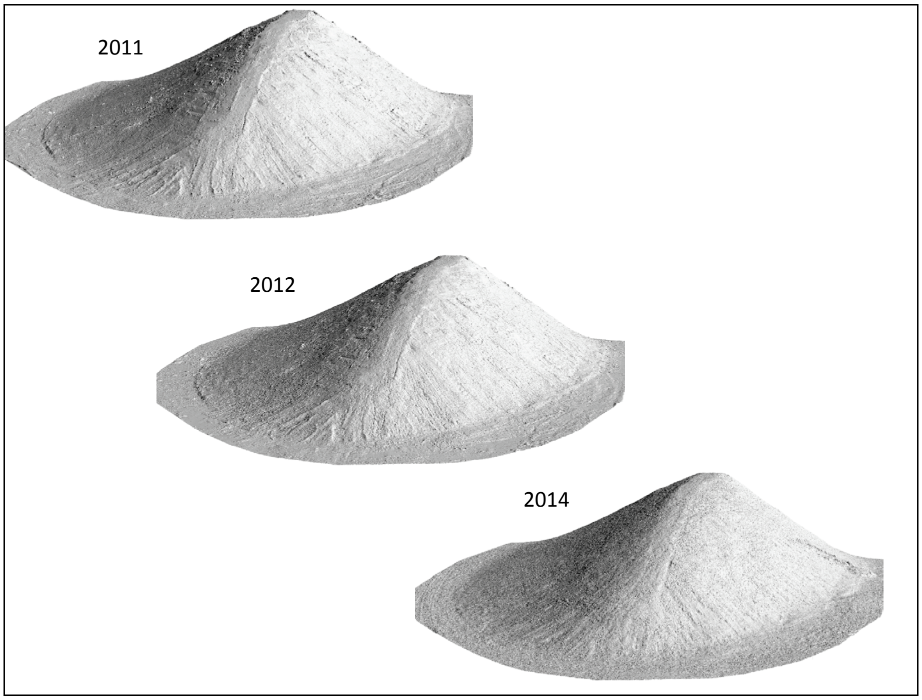


Figure 3-10. Location of soil slip in Area C of the IAAAP explosion protection berm 19 months post-treatment.

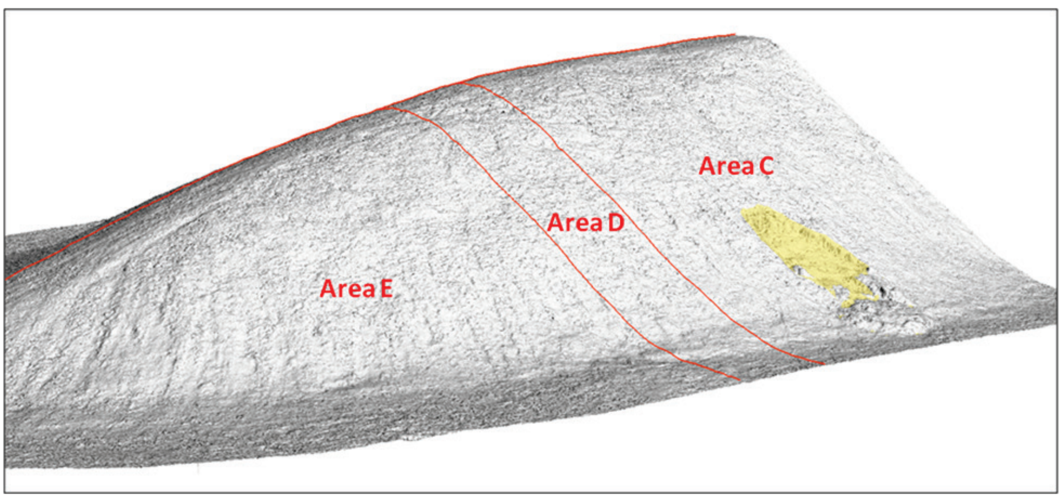


Figure 3-11. Photograph of the soil slip in Area C of the IAAAP explosion protection berm at 19 months post-treatment.

According to Kuthari (2007), each landslide begins with a slip at the weak point of the slope. When the fluctuations between the forces driving and resisting the slippage reach zero, the slip stops spreading. No sign of soil slippage or cracking was observed in any of the other biopolymer treated areas at that time. However, LiDAR surfaces generated of the crest of the berm show a small indentation (Figure 3-12), which channeled surface runoff water directly onto the area of the slip. Changes over time shown in LiDAR surface models of the area of the berm where the failure occurred are compared in Figure 3-13. The red color indicates heavy soil loss along the berm crest in the region of the indentation.

Figure 3-12. LiDAR image of the crest of the protective berm over time.

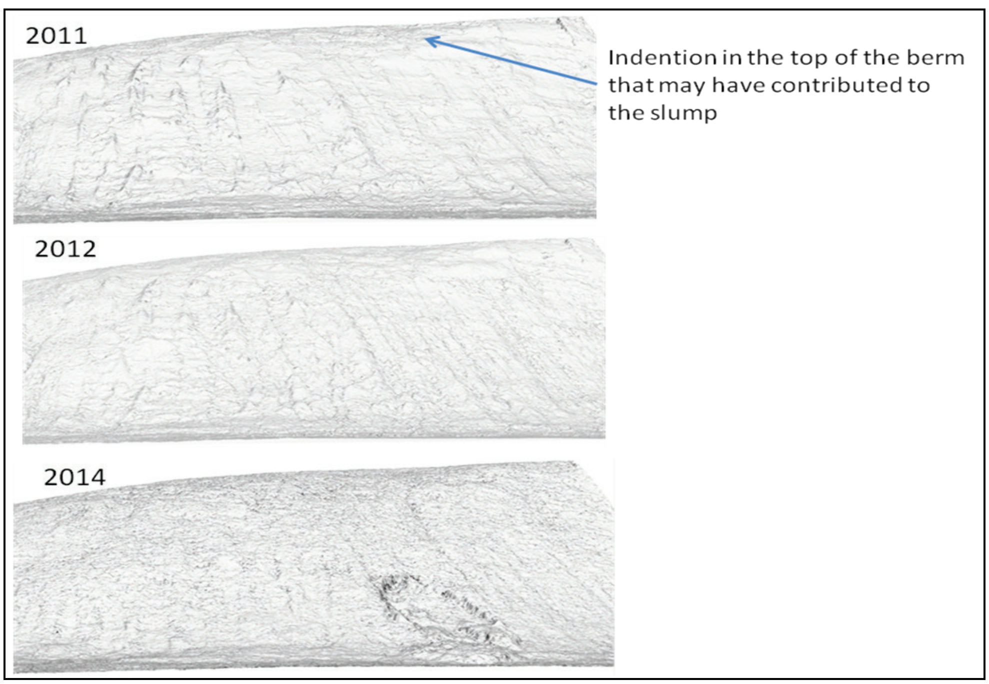
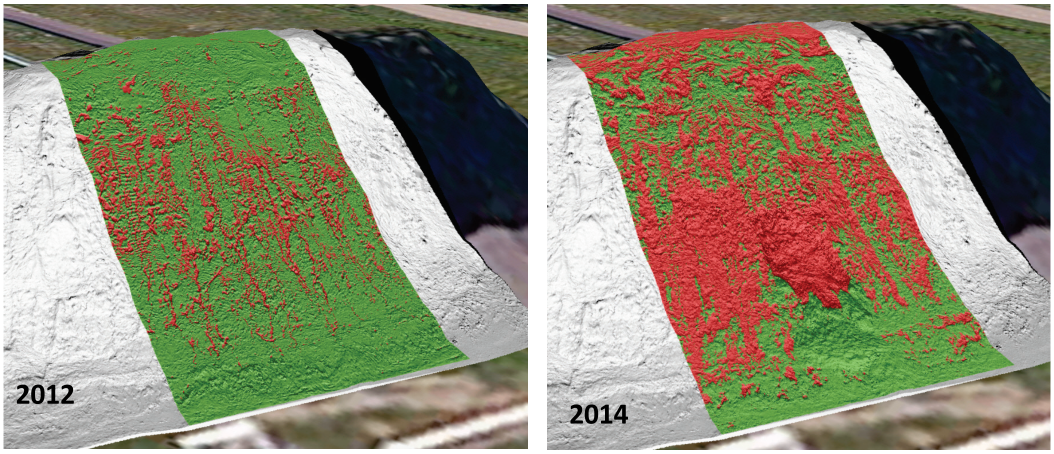


Figure 3-13. LiDAR images of the land slip from the 2012 and 2014 surveys.



According to the theory of progressive slope failure presented by Quinn et al. (2012), slope failure is associated with precipitation as well as soil type. As reported in Section 2.1.2, the average annual precipitation in Southeast Iowa is 40.6 inches, generally well distributed throughout the year. Figure 3-14 charts the monthly average precipitation, rain and snow, in relation to LiDAR surveys and the soil slip. In the six months between initial LiDAR evaluations (October 2011 to March 2012), the site received 12.93-in of rainfall and 12.4-in of snow. In the 14 month span between the March/ April 2012 LiDAR evaluation until the discovery of the landslide, the site received just over 50-in of precipitation; 7 inches in April and 11 inches in May 2013, and 25-in of snow. The rainfall that occurred in April and May 2013, was the heaviest on record during the demonstration timeframe. The soil slippage indicated on Figures 3-10 through 3-13 occurred approximately 19 months after berm restructuring and biopolymer application. The working hypothesis is that the heavy rainfall initiated the soil slippage. The unusually heavy snowfall in 2014 probably served to enlarge the slip area. LiDAR surveys supported this hypothesis indicating flowpaths of surface water runoff from the berm (Figure 3-15). This increased water flow, particularly from the crest indentation, appears to have increased the soil loss evident in Figure 3-13 above.

Figure 3-14. Monthly precipitation totals at the IAAAP during the extended field demonstration.

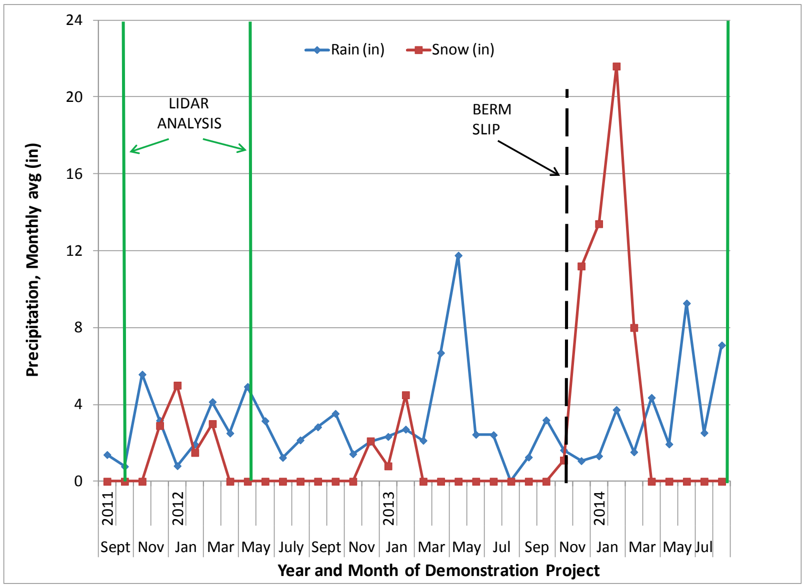
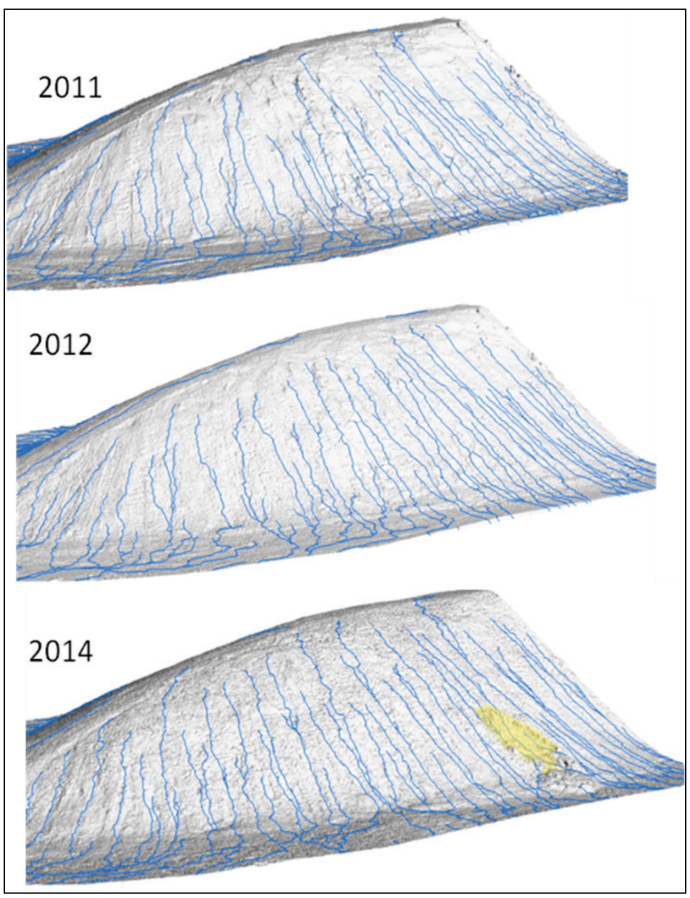


Figure 3-15. Flow pathways for surface water runoff from the berm increase in the area of the slip during the field demonstration.



4 Cost Assessment

The cost of using a biopolymer as a replacement for petroleum based polymers aimed at soil slope stabilization is dependent on the area of slope to be stabilized, the current cost of petroleum-based products, and the availability of earth moving equipment and a hydroseeder in the area to be treated. In the treatability study (Larson et al. 2012), two highly erodible soil types were amended with biopolymer at three dosing levels and exposed to both water and wind erosion. The biopolymer either equaled or out-performed petroleum-based polymers in protection from both wind and water erosion. The field demonstration used the best performing biopolymer amendment and examined alternate application methods, using LiDAR imaging to evaluate slope stabilization over time.

Stabilization of the explosion protection berm at IAAAP was a full-scale field demonstration. The contractor costs are documented in Table 4-1 and Table 4-2 for the earth-moving activities and the biopolymer, respectively. These costs are detailed in the project Cost and Performance report on the ESTCP website (www.estcp.org) for ER-200920 (Larson et al. 2014).

Berm construction costs (Table 4-1) were based on the rental of a bulldozer and payment to the equipment operator and a laborer for two 14-hr days. Both the bulldozer and hydroseeder had a delivery surcharge; however, the contractor purchased the necessary fuel ($1800) and an additional 100 yd^3 of soil at $25/$yd^3$. The soil was used to reconstruct the berm to its original specifications.

Table 4-1. Costs to construct and seed the explosion protection berm at the IAAAP.

Item	Hours	$/hr	Days	$/day	Additional cost	Total ($)
Dozer operator	28	45				1,260.00
Laborer	28	30				840.00
6-way blade dozer			2	1000		2,000.00
Hydroseeder			2	1000	1800	3,800.00
Additional soil					2500	2,500.00
Per diem labor operator					1920	1,920.00
TOTAL						**$12,320.00**

Table 4-2. Costs of biopolymer production and delivery.

Item	Gal	$/gal	Additional cost ($)	Total ($)
R. tropici biopolymer production	11,000	5.00		55,000.00
Delivery	11,000	1.10	7,000*	19,100.00
Travel			2,500**	2,500.00
TOTAL				**$76,600.00**

*Tanks were required to remain on-site for two days

**Three days travel for contractor

Costs for the entire project are summarized in Table 4-3. Note that this is an inclusive cost detailing for the project and most sites will require only basic, or no, soil characterization and testing prior to deployment of the biopolymer (Treatability Study, Larson et al. 2012). The soils of many military and civilian sites where this technology could be applied have already been characterized to support construction, maintenance, or ongoing monitoring. If there is a question, minor treatability costs incurred prior to installation would determine the optimal biopolymer dosage.

Table 4-3. Cost for Berm Slope Stabilization using Biopolymer (Larson et al. 2014).

Cost Element	Data Tracked During the Demonstration			Total Cost ($)
ESTCP Treatability Study	• Labor	Engineer	40 hr	8,000
		Engineer technician	80 hr	4,800
	• Travel	Sample collection		2,500
	• Materials	Lab supplies		1,000
	• Analytical laboratory costs			5,000
	Total treatability study			**21,300**
Material cost	• $ per gal of biopolymer	$ provided by vendor	5.00	
	• 11,000 gal needed based on surface area to be treated			55,000
	• Additional soil for re-contouring berm			2,500
	Total material cost			**57,500**
Installation	• $ per gal of biopolymer	$ provided by vendor	1.10	
	• Delivery costs			19,100
	• Dozer rental (2 days)			2,000
	• Hydroseeder (2 days)			3,800
	• Labor			4,020
	• ETS per diem travel			2,500

Cost Element	Data Tracked During the Demonstration			Total Cost ($)
Waste disposal	• No waste disposal required			NA
Operation and maintenance costs	• No unique requirements			NA
Long-term monitoring	• No cost tracking			NA
Total Installation Cost				**31,420**
Total Technology Cost				**110,220**

The majority of the costs associated with the biopolymer slope stabilization are material costs and labor, which includes production of the biopolymer and applying it to the slope.

- The quantity of biopolymer required for slope stabilization is based on soil type and size of the area to be treated. The biopolymer works well at low dosing rates for silty sand and silt soil types. The biopolymer is less successful stabilizing soils with large, heavy grain sizes, such as sand and glacial till. For these soil types, a higher dosing rate is required. For slope stabilization, a dosing rate of 0.5% has been successful with the majority of soils studied. The material costs scale linearly with increasing area to be treated. Freight costs for delivery to the site is dependent on the distance from the manufacturing plant, but biopolymer can also be delivered in a dry state, which reduces the cost of shipping. For smaller projects, or projects that will be staged in several areas, the biopolymer can also be delivered in 55-gal drums. This would avoid the added charge for keeping the delivery tanks on site overnight. A commercial source and CRADA partner, ETS, Inc., delivered the biopolymer used in this demonstration to the project site.
- Equipment and labor costs depend on the availability of such from the activity sponsor. In the case of the IAAAP field demonstration, the equipment was not available on-site and had to be rented, along with the additional costs of delivery charges. However, many installations have access to earth-moving equipment and hydroseeders with trained operators. Labor must still be accounted for, and this may be overtime work depending on the situation. For example, if slope maintenance must be done on the weekend, scheduling and additional labor costs must be taken into account. The labor of adding biopolymer will not be a great additional expense. For this field demonstration, additional soil

had to be purchased by the contracting company in order to restructure the explosion safety berm to the original specifications. If soil for this purpose was available on-site, this cost would only be reflected in labor. This is also a non-recurring cost.

The field demonstration did not incur permitting or environmental reporting costs, and do not expect these costs to impact future projects. The biopolymer is non-toxic and, ultimately, biodegradable. The Material Safety Data Sheet (MSDS) for the biopolymer is presented in Appendix A. Bacteria was not applied to the soil, as the exopolymer was separated from the bacteria during processing. In addition, waste disposal costs were not incurred.

In summary, the major cost drivers for implementing this technology are:

- biopolymer production and delivery to the site
- availability of heavy earth-moving equipment and trained operators for berm/slope construction/re-construction,
- availability of a hydroseeder for application of the biopolymer and grass seed. If these items need to be rented, the cost of technology implementation increases.

Soils with little organic matter or nutrient content may need to be supplemented with compost and/or fertilizer prior to re-vegetation.

A cost analysis comparison can be made to a traditional berm (sloped soil structure with grass) with a 30-year life span. This cost analysis assumes that the installation provides heavy equipment and operators. The cost of the biopolymer is based on gal/ area of soil surface to be treated. Comparative costs for construction and maintenance of a traditional earthen berm are shown in Table 4-4. The costs were adjusted for inflation and reflect 2012 rates.

The cost of building and maintaining a berm with a single application of biopolymer is approximately half (0.52) of what it costs for a traditional earthen berm over a 30-yr period. Construction costs are lower because:

- there are no remobilization costs for return visits to the site to repair early rutting and other erosion problems
- there are no re-grassing issues that require remobilization of hydroseeders and purchases of fertilizer and seed.

Although budgeted (Table 4-4), there have been no yearly O&M costs incurred with the biopolymer-treated slopes over the last three years. This further increases the cost: benefit ratio over traditional earthen berms.

Table 4-4. Comparative cost of construction and maintenance of an earthen berm and a biopolymer-treated berm based on 100 feet of berm.

Cost Parameter	Earthen Berm (grassed) ($2012)	Biopolymer-Treated Berm (grassed) ($2012)
Construction	134,973	90,787
Yearly O&M[a]	6,210	2,553
Years in Operation	30	30
30 Yr O&M cost	186,300	76,590
Overhaul at 10 yr[b]	67,487	35,143
Number of overhauls	2	2
Cost for overhaul	134,974	70,286
30 yr Total Cost[c]	456,247	237,663

[a]Estimated cost of soil addition and re-grassing to repair slope degradation

[b]For the biopolymer-treated berm, this is conservatively estimated at half the biopolymer cost and one day of labor and equipment rental (Table 4-3)

[c]All costs adjusted for inflation to $2012

5 Conclusions

This field demonstration met all performance objectives. The following conclusions were made:

- The biopolymer treated areas maintained the height of the explosion protection berm for over three years without maintenance.
- The most effective biopolymer application method, as judged by soil mass lost and elevation analysis, was the double application at depth. The second most-effective treatment was the double surface application.
- All biopolymer-treated areas reduced the amount of soil lost from the berm. The least soil mass lost was observed in the double application at depth (17% compared to the control).
- All biopolymer-treated areas significantly reduced surface roughness (11% to 28% of control). Surface roughness can be indicative of the development of erosion gullies.
- All biopolymer-treated areas showed an increase in biomass over the control at one month. Observation showed that all treated areas continued to be well grassed after 30 months.
- Although budgeted in the cost analysis, there have been no yearly O&M costs incurred with the biopolymer, including mowing, which further increases the cost: benefit ratio over traditional earthen berms.
- Based on the positive feedback from the field technicians concerning time and effort required for biopolymer application, as well as the manufacturer estimates of application times, the treatment was successful.

Biologically produced polymers have a number of unique benefits when compared to petrochemical-based polymers, beyond the reduction in use of chemicals derived from oil. Because biopolymers are produced as a result of complex biosynthesis by bacteria and algae, their polymeric structure is more diversified than the regularly recurring units in traditional plastics. This provides enhanced functionality, including post-application cross-linking, ease of derivitization for specific uses, and a long-lived, but ultimately biodegradable, material without the environmental concerns associated with synthetic polymers (Cabaniss et al. 2005, Decho 2009, Goto et al. 2001). In addition, the use of these materials acts as a carbon

storehouse for readily biodegradable sugars that would otherwise be oxidized to CO_2 and contribute to elevated greenhouse gasses in the atmosphere. Biopolymers have been shown to be effective alternatives for the petrochemical-based polymer soil additives currently in use.

The explosion protection berm at IAAAP was actively monitored for six months. Telephone communication and electronic monitoring were used after that time. LiDAR evaluations were conducted at one and six months, during post-treatment, and a final assessment after three years. The biopolymer-treated areas showed no change in slope over the first six months. Personal observation and discussion with IAAAP personnel confirmed that the treated slopes were also well grassed. However, the double application area showed soil cracking after six months. A landslip occurred 20 months after treatment in the area of the double surface application. The remaining biopolymer-treated soils have now remained stable for over 36 months. The soil collapse increased slightly in size until a stable slope was achieved (S. Bellrichard, 2014, *personal communication*). A comparison of LiDAR survey data over three years indicates an indentation in the crest of the berm and an increase of surface water flow in the area of the collapse.

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Appendix A: MSDS for *R. tropici* Biopolymer

ETS Environmental Technology Solutions

Material Safety Data Sheet

Environmental Technology Solutions **75 W. Baseline Rd. Suite 32** **Gilbert AZ, 85233**	**In Case of Emergency, Call** 1 480 648 1849
Date of MSDS Preparation 4/3/2011	**Superseded date** Original
MSDS Prepared By: G. Nijak	**For further information contact** 1 480 648 1849

Section 1: Product Identification

Product Identifier:	GreenTac	**Active Ingredient (%):**	
Registration No.:	Not Applicable	**Chemical Name:**	
Chemical Class:		**Product Use:**	Water Retention, Dust Suppressant
Synonym:	Absorbent, Suppressant		

Section 2: Composition/Information on Ingredients

Material	OSHA PEL	ACGIH TLV	NTP/IARC/OSHA Carcinogen	WHMIS
Poly Saccharide	None	None	No	NA
Yeast Extract	None	None	No	NA

Section 3: Hazards Identification

Symptoms of Acute Exposure:	Generally not hazardous in normal circumstances. However, good practices should always be followed. Avoid excessive exposure to skin and eyes
Hazardous Decomposition Products:	None known
Physical Properties:	Light to dark brown, Musky odor, Viscous
Unusual Fire, Explosion, & Reactivity Hazards:	None
Potential Health Effects:	May cause irritation of the eyes with prolonged exposure. May cause irritation to exposed skin and respiratory tract.

Section 4: First Aid Measures

Eye Contact: Wash with water and seek medical assistance if irritation persists.

Skin Contact: Wash exposed area with soap and water. If any irritation persists, seek medical attention.

Inhalation: Remove to fresh air.

Ingestion: No known hazards. Drink water to dilute possible ingestion related problems

Note to Physician: None

Medical Conditions Known to be Aggravated: None

Section 5: Fire Fighting Measures

Flash point & method:	NA
Upper & lower flammable (explosive) limits in air:	NA
Auto ignition temperature:	NA
Hazardous combustion products:	NA
Conditions under which flammability could occur:	None
Extinguishing media:	NA
Sensitivity to explosion by mechanical impact:	None
Sensitivity to explosion by static discharge:	None

Section 6: Accidental Release Measures

Personal Precautions:

Avoid exposure to eyes and skin. Wear safety glasses to prevent splashing the product into eyes. Where there is a likelihood of product dust, the use of NIOSH approved respirator is recommended.

Procedures for dealing with release or spill:

If spilled, mop up and use or dispose. Product when in liquid form will be slippery. Water will dissolve and dilute until it is no longer slippery.

Section 7: Handling & Storage

Handling Practices:

Avoid unnecessary exposure, especially to the eyes. Wear eye protection and wash exposed skin after handling the product. General ventilation is usually adequate for the handling of this product.

Appropriate storage practices/requirements:

Keep material sealed until ready for use. Use good practices to avoid spilling in undesired areas.

National Fire Code classification:

NONE

Section 8: Exposure Control/Personal Protection

Applicable control measures, including engineering controls:

Generally, this is not a hazardous material. Good hygiene practices, general ventilation and appropriate eye protection is adequate for most handling situations.

Personal protective equipment for each exposure route:

General:

Ingestion: Wear dust mask when handling.

Eyes: Glasses with side shields or chemical goggles as appropriate to the handling circumstances.

Skin: Use safety gloves as with any chemicals.

Inhalation: None normally required. If dust possible, a NIOSH approved respirator should be worn.

Section 9: Physical & Chemical Properties

Appearance:	Light to dark brown	**Vapor Density:**	NA
Formulation Type:	Liquid	**Boiling point:**	>150°C
Odor:	Musty	**Melting point:**	NA
pH:	10.5	**Freezing point:**	NA
Vapor pressure and reference temp:	NA	**Specific gravity or density:**	NA
Evaporation Rate:	NA	**Viscosity:**	10.1 cP
Odor threshold:	NA	**Solubility in Water:**	81 g/L (time limited)

Section 10: Stability & Reactivity

Chemical Stability:	STABLE
Conditions to avoid:	NA
Incompatibility with other materials:	Strong acids
Hazardous decompositions products:	None
Hazardous polymerization:	May not occur

Section 11: Regulatory Information

WHMIS Classification for Product: This product is not a controlled material.

Canadian DSL: The ingredients in this product are on the Domestic Substance List.

REPORT DOCUMENTATION PAGE

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2. REPORT TYPE
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Evaluation of Rhizobium tropici-derived biopolymer for erosion control of protective berms: Field Study: Iowa Army Ammunition Plant

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Approved for public release; Distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A Rhizobium tropici-produced biopolymer was applied to an explosion protection berm at the Iowa Army Ammunition Plant (IAAAP) to stabilize the soil, prevent loss of berm height, reduce erosion, and increase the rate and extent of revegetation. The berm was recontoured, and a hydroseeder was used to apply biopolymer with grass seed. The control area received plain water and seed. Evaluated biopolymer application methods include: single surface application, double surface application, and a double application at depth, with the first application 2-ft below ground surface (bgs), and the second on the surface. A LiDAR (Light Detection and Ranging) survey evaluated soil movement from the berm slope over three years. The double application of the biopolymer at depth was the most effective application method as determined by calculating soil loss and surface roughness, followed closely by the double surface application. At 19 months post-treatment, a landslip was observed in the treated area that received the double surface application of biopolymer. There was no evidence of soil cracking in any other treated areas.

15. SUBJECT TERMS

Biopolymer
cost evaluation
erosion control
extracellular polymeric substance (EPS)
field demonstration
LiDAR survey
re-vegetation
slope stability
soil additive
soil stabilization

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